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DETERMINATION OF THE ELASTICITY OF PARACHUTE MATERIALS UNDER DYNAMIC LOADING CONDITIONS

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ABSTRACT

In the design of parachute systems it is important to use material properties that have been acquired under representative strain rates expected in flight. Without such data the designer is potentially forced to incorporate unrealistic safety margins resulting in a heavier and costlier than required design. Laboratory test data has generally been limited to that which can be acquired at quasi-steady strain rates. This paper investigates a technique, which takes advantage of advances in solid state electronics in the past ten years, to achieve an economical means of acquiring material properties under dynamic strain conditions. Data obtained with this technique is compared to standard test data for representative parachute materials.

INTRODUCTION

Past works have suggested that the properties of textile materials obtained through the typical quasi-static testing process are inapplicable to a high dynamic application[1, 2, 3]. Representative standards[4, 5, 6] for testing the ultimate strength of textiles call for a tensile test machine operating at strain rates of 0.0015-0.005 sec^{-1}. During snatch loads in parachute systems, the strain rate can be many orders of magnitude greater than this. At this much higher strain rate, the individual yarns are limited in how much they can move to equalize the load and a much different modulus of elasticity may apply.

Testing materials at representative high strain rates requires much more sophisticated and expensive equipment than found in a typical material testing lab. For smaller companies on restricted budgets, this can be a prohibitively expensive option. Thus, either some other means of determining the high strain rate elasticity must be found, or quasi-static properties must be used. Using quasi-static properties may require gross over design of certain critical components or result in unexpected system failures. Neither of these options is attractive from a systems optimization/budget point of view. This paper describes a low-cost alternative for obtaining more representative material properties for use in high strain rate environments.

Some evidence has also been presented in the past that woven materials perform differently when loaded the first time than they do during subsequent uses. This has implications regarding material selection for decelerator systems that are designed for multiple uses. As a means of addressing this question, multiple test articles were made of like construction and tested to get a good statistical sampling of first time loading behavior. Then individual articles were tested repeatedly to investigate the effects of multiple loadings.

TEST APPARATUS

Drop Tests

The advances in solid state electronic technology in the past ten years has allowed for increasingly complex solid state data acquisition devices to be built. These devices have advanced to the point that data can now be acquired at sufficiently high rates and over long enough times to be applied to the snatch load problem. They can even be set up to trigger on a minimum acceleration and take data for a prescribed time after the trigger event. These types of devices have already been flown in parachute

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systems in various development programs and have provided valuable post-flight data.[7] The broadening field of use has resulted in the cost reduction of these devices to very affordable levels. By using these devices, it is very easy to perform some lab tests which can more closely simulate the strain rate in a typical snatch load situation.

Two different experimental devices were used for this study to obtain properties of and demonstrate the effects of strain rate on representative materials used in construction of parachute systems. One of these was a commonly used tensile test machine, an Instron Model 4507. Due to the strain rate limitations of the tensile test machine (< 0.005 sec^{-1}), another, non-conventional, scheme was used to obtain data at higher strain rates.

The non-conventional scheme involved dropping an instrumented platform and "snatching" it with a piece of representative parachute webbing after it had fallen a known distance. By measuring the peak accelerations and acceleration profiles and knowing the weight of the platform and the fall distance, the force versus strain nature of the material could be back calculated. A picture of the test setup just before the platform is dropped is shown in Figure 1.

The instrumented platform can be seen in Figure 2. Mounted on the centerline of the platform is a commercially available EDR-1 Environmental Data Recorder.* The EDR-1 recorded data at 3200 samples per second up to a maximum of 65 g's on all three axes. The EDR-1 is capable of remote, stand alone acceleration measurements and has an internal storage capability of 1 megabyte. The EDR-1 is completely programmable using a personal computer. It may be programmed to be event or time triggered for recording. Once triggered, digital recording of data from the three internal accelerometers takes place. Each recorded event is time and date tagged.

After the EDR-1 was dropped the first few times, it was found that the peak accelerations frequently exceeded the device's 65g maximum. This was especially true when testing the stiffer Kevlar materials. Rescaling the EDR-1 to a larger dynamic range was not possible due to time constraints. However, another device was available which would measure the peak acceleration on a single axis, this being the SnapShock 2000.* Since a SnapShock 2000 could not be mounted on the center of gravity of the EDR-1, two were mounted on the platform, one on either side. This allowed the peak accelerations recorded by each to be averaged in an attempt to eliminate the contribution of rotational acceleration if the platform had rotated during it period of free fall. This also allowed the peak acceleration to be captured even when the EDR-1's accelerometers saturated.

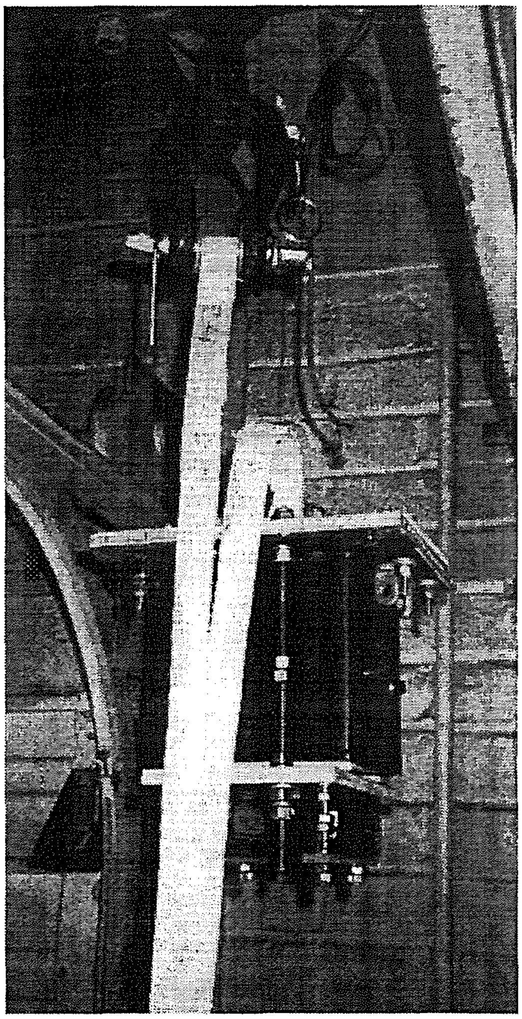

Figure 1. Drop Test Apparatus ready for a Test

The SnapShock 2000 is battery powered and records the time and date that each peak acceleration is recorded. The device senses and records the peak acceleration that occurs within a preprogrammed "time bin". A time bin of 4.47 seconds was used for these tests. As in the case

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of the EDR-1, the SnapShock 2000s were programmed and data retrieved with a personal computer. The devices had a maximum range of 500 g's with 1.3 g resolution.

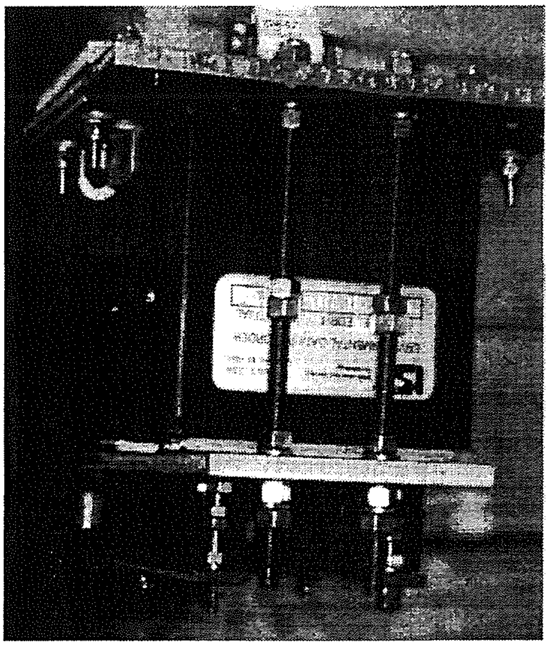

Figure 2. Close-up of Instrumented Platform

The procedure for the "drop" tests involved the following steps:

1. One end of the material strap of interest was attached to the instrumented platform and the other end to an "I' beam at ceiling level.
2. The instrument platform was suspended near "I" beam level with a temporary tie and the suspended height measured.
3. The instrumented platform was tapped with a hammer as the "event" to start the EDR-1 recording.
4. The temporary tie was cut and the instrumented platform allowed to fall until being "snatched" by the webbing of interest.
5. Data was downloaded from the EDR-1 and SnapShock 2000s.
6. The at-rest height of the platform was measured and recorded.

Tensile Tests

The same materials were tested in a tensile test machine at relatively low strain rates. The standard for textile tests of tapes and webbings calls for using the capstan clamps during the test. These clamps make it very difficult to use the machine to calculate the modulus of the material since the gauge length and elongation are hard to relate to jaw position and are not even necessarily fixed in a given test.

Grip clamps provide better control over the gauge length and hence a machine based elongation calculation is more meaningful. However, slippage in the jaws results in errors in the gauge length and the material frequently breaks at the edge of the clamps at a load much less than observed in tests using capstan clamps. This premature breakage is due to the stress concentration developed due to the grip clamps.

Another, more accurate means of determining the modulus is to mark a known length at zero or nominal load and measure the extension of that initial length as load is applied. Several means of doing this have been devised over the years, including electrical potentiometers attached in the gauge region and optical scanning techniques. Neither of these techniques were available for these tests, so a more fundamental method was used. Lines were marked on the material, at the edges of the jaws. During the tests, the lines were observed as witness of any slippage of the materials out of the clamps. At the end of the test, the total amount of slippage was measured to correct the machine-generated displacements back to actual elongation values.

The data was then plotted and the slope of a least squares curve fit used to calculate the modulus. This method worked quite well for Nylon, which undergoes significant strain before reaching rated load and tends to slip out of the grips uniformly as the load increases. However, it is less accurate for the much stiffer Kevlar materials. The Kevlar materials tended to slip in a quantum fashion as will be seen in the test results when they are presented.

THEORY

To model the drop tests, we need to consider a line made of the sample material that is attached to a "rigid" attachment point on one end and to a known mass on the other. The mass is suspended some distance above the point at which the line goes taut. Upon release, the mass free falls until the sample material goes taut and brings the mass to rest.

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Summing all the forces on the mass (after the line has gone taut) and applying Newton's first law and the constraint of constant mass gives:

$$\sum F = \frac{d}{dt}(mV) \tag{1}$$

$$mg - F_{line} = m\frac{dV}{dt} \tag{2}$$

Where:

t = time,

V = Velocity of the mass,

m = Mass of body being dropped,

F_{line} = Force exerted on mass by line, and

g = acceleration due to gravity.

Substituting for V in terms of the position, x (from the position of the mass at the time the line has just gone taut), and rearranging yields:

$$\frac{d^2x}{dt^2} + \frac{F(x)}{m} = g \tag{3}$$

Now if we assume the line acts like a simple spring such that

$$F(x) = kx \tag{4}$$

Where k is the spring constant, we are left with:

$$\frac{d^2x}{dt^2} + \frac{k}{m}x = g \tag{5}$$

This is a non-homogeneous, second-order, ordinary differential equation which with the boundary conditions, $x(t=0)=0$ and $x'(t=0)=V_0$, can be shown to have the solution:

$$x = \frac{g}{\omega^2}(1 - \cos\omega t) + \frac{V_0}{\omega}\sin\omega t \tag{6}$$

where:

V_0 = $\sqrt{2gh}$, the velocity of the mass when the line goes taut due to it falling through distance h, and

ω = $\sqrt{\frac{k}{m}}$, the natural frequency of the system.

From this equation we can solve for the maximum extension of the line which corresponds to the maximum force in the line. Thus, the maximum acceleration of the mass during the period the line goes taut can be found by solving for x when $x'=0$. Doing so yields:

$$x_{max} = \frac{V_0}{\omega}\left(\frac{g}{V_0\omega} + \sqrt{\left(\frac{g}{V_0\omega}\right)^2 + 1}\right) \tag{7}$$

Thus, the maximum force to be observed in the line should be:

$$F_{max} = kx_{max} \tag{8}$$

and the maximum acceleration expected in the mass is:

$$a_{max} = \frac{F_{max}}{m} = \frac{kx_{max}}{m} \tag{9}$$

Thus, by knowing the drop height of the mass, the length of the line, and the mass of the object dropped we can predict the maximum acceleration of the object if we only know the spring constant of the material. Or, alternatively, if we measure the maximum acceleration of the dropped object, we can calculate a simple spring constant to describe the material. This will be pursued in the next section.

It should be noted that if gravity can be ignored during the period after the line has gone taut, the equation for x_{max} can be simplified to:

$$x_{max} = \frac{V_0}{\omega} \tag{10}$$

We can see from the original equation that this is a valid simplification if:

$$\frac{g}{V_0\omega} << 1 \tag{11}$$

This is analogous to saying that the energy introduced into the system due to gravity in the course of travelling one wavelength of the system is much less than the initial kinetic energy of the mass when the line first goes taut. Since the kinetic energy of the system is due to the mass falling the distance h and in our experiments the line

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stretched much less than h, this is a valid assumption and the reduced equation can be used.

The spring constant for the line can be defined in terms of the length of the line and the material modulus as:

$$k = \frac{E}{L} \tag{12}$$

where:

E = the modulus of the material (lbf/in/in), and

L = the length of the line.

The modulus of the material is defined here as the average slope of the load strain curve over an appropriate range of loads. Thus, we can solve for E in terms of the measured peak acceleration (a_{max}), the drop height (h), the mass of the platform (m), and the strap length (L) and obtain:

$$E = \frac{m a_{max}^2 L}{2gh} \tag{13}$$

This equation can be used to calculate the material modulus based upon the accelerations measured in the drop tests.

RESULTS

The snatch load between two moving objects connected by a line can be shown to be:[8]

$$F = \Delta V \left(\frac{k m_1 m_2}{m_1 + m_2} \right)^{1/2}$$

where:

ΔV = the magnitude of the difference in velocity of the two masses,

k = the spring constant for the material as defined previously, and

m_i = the mass of object i.

The spring constant of the line is related to the modulus of the material and the length of line as shown in equation (12). Thus, it is useful to compare the different values of material modulus obtained from the various means of test.

Strain-at-Break Based Modulus

The simplest way of calculating the modulus of a material is by using typically quoted numbers of strain at break for Nylon and Kevlar along with the rated strength of the material. The modulus calculated in this manner will be included for discussion purposes. It is quite common to hear that Nylon tapes and webbings achieve 20% strain and Kevlar 5% strain at their rated load. Other references[8, 9], quote ranges of 25-40% and 3-5% for Nylon and Kevlar, respectively. For the Nylon webbing rated at 12,000 pound breaking strength (lb-brk-str) used in this study, this strain range (20-40%) results in a modulus range of 30,000 to 60,000 lbf/in/in. For the 13,500 lb-brk-str Kevlar webbing used, we obtain a modulus range of 270,000 to 450,000 lbf/in/in. It is important to note that the quoted strains are for the parent Nylon and Kevlar yarns and that we expect to see differences when measuring the properties of woven materials. However, it is instructive to compare the quasi-static and snatch data to these ranges.

Tensile-Test Based Modulus

Three samples of both the 13,500 lb-brk-str Kevlar and 12,000 lb-brk-str Nylon webbings were tested in a tensile test machine. The observed load as a function of head travel is shown in Figures 3 and 4.

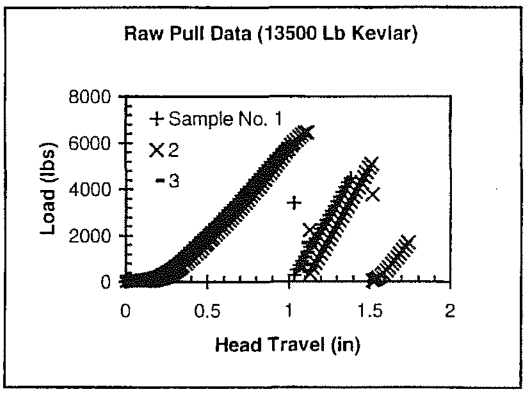

Figure 3. Results of Tensile Tests on 13,500 Lb-Brk-Str Kevlar

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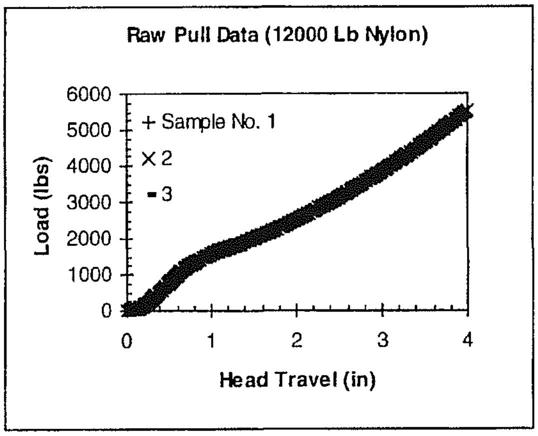

Figure 4. Results of Tensile Tests on 12,000 Lb-Brk-Str Nylon

The tests, which produced the data presented in Figures 3 and 4, utilized grip clamps in the tensile test machine. Normally capstan clamps are used for the testing of tapes and webbings where the parameter of most interest is ultimate breaking strength. The capstan clamps avoid the problem of breaks at the edge of the jaw clamps, but leave the user with an ambiguous value of gauge length unless other measurements are made separate from head travel. With grip clamps, if there is no slippage, the elongation is the head travel, the gauge length is well known and thus strain can be calculated readily.

Looking at Figure 3, we can see two regions where the load drops off precipitously. This is due to quantum slips of the Kevlar materials in the grip jaws at the higher loads. This is a common characteristic of testing Kevlar materials due to the very low elongation properties. However, very little if any slippage was noted between these discrete events. The initial ramp up in the data associated with the first 0.3" of head travel could be due either to initial "setting" of the grip clamps into to the webbing or due to initial compression of the weave upon itself. If the slope of the nearly straight-line portions of the curve before the first slip is used, a modulus of 179,000 lbf/in/in is calculated. If the slope of the curves after the first slip is used a modulus of 287,000 lbf/in/in is calculated. Why the slope of the curve changes so much after the first slip is not understood at this time.

Looking at Figure 4, we do not see any obvious slippage for the Nylon samples. The repeatability of the data is amazing in itself. However, as the samples were loaded it was observed that the material was slowly slipping out of the grips as the load increased. This slow even slippage is more characteristic of Nylon than the quantum slips in Kevlar due to Nylons larger elongation properties. The amount the webbing had moved relative to the grips was measured and subtracted off of the final maximum head travel in an effort to account for the slippage. Using a least squares fit to the data shown in Figure 4, moduli of 23,800 and 27,200 lbf/in/in were calculated with no slippage correction and with a slippage correction applied, respectively.

Drop Test Based Modulus

Using the equations developed earlier, the peak acceleration from the drop tests, the length of the material, and the drop height can be used to calculate a modulus for the material. The calculated modulus for each of the drops can be found in Tables 1 and 2 for the Kevlar and Nylon material, respectively. This data has been plotted in Figures 5 and 6 as a function of the number of previous drops to observe the effects of prior loading of the straps. We can see by observing Figure 5 that the Kevlar material may exhibit a slight increase in modulus over the first three drops, although the trend in the data may not be large enough compared to the uncertainty to be statistically significant. Similarly, the data for the Nylon material is shown in Figure 6. This data shows no significant trend in the modulus with respect to the number of prior drops. Ignoring any dependency of the modulus on the number of drops, an average value can be calculated for all the drops of a given material and compared to the values obtained by the Tensile-Test Method and the Strain-at-Break Method. This comparison can be found in Table 3

CONCLUSIONS & RECOMMENDATIONS

At the outset of this investigation, five different strength webbings of Nylon and Kevlar were intended to be investigated. Time did not permit this to occur and we are left with only a fraction of the data set originally intended. Within this limited data set, one must be careful in drawing conclusions regarding the materials themselves. However, some things have been learned that can be expanded upon.

In future tests, the dynamic range of the EDR-1 recorder should be increased. By doing so, an acceleration-time history can be obtained from the EDR-1 that does not saturate the instrument. With such a history, the entire strain vs. load history could be reconstructed using

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Table 1. Modulus from Drop Tests of 13,500 Lb-Brk-Str Kevlar Webbing (lbf/in/in)

		Strap S/N			
		1	3	7	8
Prior Drops	Drop Height (ft)	7.40	7.54	7.46	7.43
0		165000	158000	118000	137000
1		189000	174000	148000	160000
2		201000	174000	162000	159000
3		184000	197000	165000	165000
4		197000	193000	150000	177000

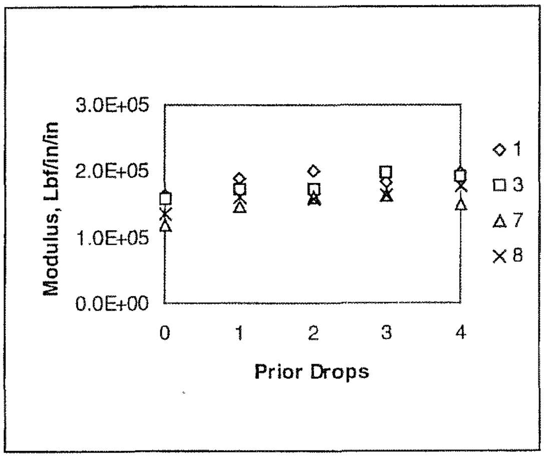

Figure 5. Modulus for 13,500 Lb-Brk-Str Kevlar Webbing Calculated from Drop Test Data

Table 3. Comparison of Material Moduli Obtained by Different Methods (lbf/in/in)

Method	12,000 Lb-Brkg-Str Nylon	13,000 Lb-Brkg-Str Kevlar
Strain-at-Break	30,000-60,000	270,000-450,000
Tensile Tests	23,800-27,200	179,000-287,000
Drop Tests	28,800-40,500	118,000-201,000

Table 2. Modulus from Drop Tests of 12,000 Lb-Brk-Str Nylon Webbing (lbf/in/in)

		Strap S/N		
		5	9	10
Prior Drops	Drop Height (ft)	7.59	7.55	7.51
0		35700	28800	29500
1		40500	30000	31000
2		39600	31500	33200
3		32600	31500	33200
4		38000	31500	33200

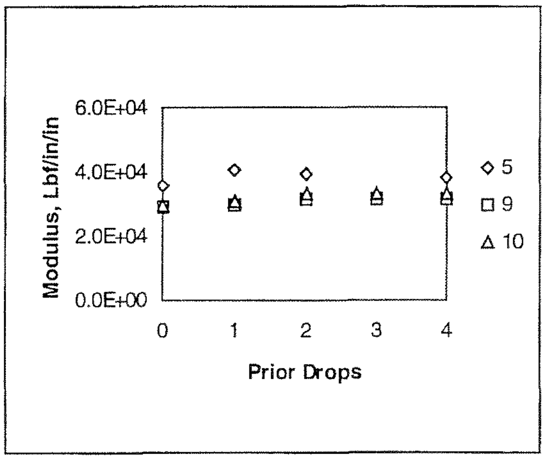

Figure 6. Modulus for 12,000 Lb-Brk-Str Nylon Webbing Calculated from Drop Test Data

numerical methods. This type of data would be much more useful than a constant modulus like was generated in this paper.

We see that for these materials there appears to be little effect of any prior loadings on the material behavior for Kevlar and virtually none observable for the Nylon. However, this is a result that may be dependent upon the specific weave of any material and caution is urged in extending this observation generically for all Kevlar and Nylon materials.

The modulus calculated based upon corrected strain data from the tensile test machine, when compared to that from the drop tests, shows that for Nylon, the material acts stiffer at high strain rates. For Kevlar,

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the limited data support no such conclusion. This is consistent with some prior statements regarding these two materials[10]. However, it is clear for both Nylon and Kevlar, that calculating a modulus based upon typically quoted values of strain at break will yield a much higher modulus than the material actually has. This could lead to over-designing of system components ultimately resulting in increased weight and costs.

It is recommended that these tests be extended to include a larger sample of tapes and webbings to gather useful information for the parachute system designer. It is also recommended that the EDR-1 be resized to provide coverage throughout the full-anticipated acceleration spectrum.

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